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Isotopic Exchange in the Platinum-Catalyzed Reductions of Olefins in Protic Solvents[1]

T. Randall Lee and George M. Whitesides*

Contribution from the Department of Chemistry, Harvard University, Cambridge, Massachusetts 02138. *Received September 10, 1990*

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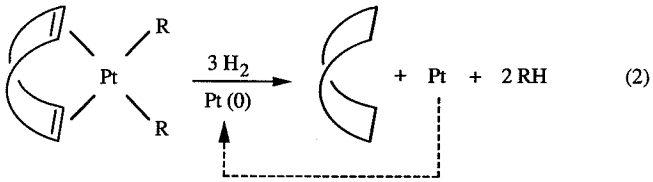
Abstract: This paper reports the isotopic compositions of alkanes obtained by the catalytic reductions of olefins using H_2 or D_2 and platinum black in alcoholic and mixed organic/aqueous solvents. The isotope found in the product alkanes was predominantly that present in the solvent (RO*H* or RO*D*) regardless of the isotope present in the gas (H_2 or D_2). The rate of exchange of isotopes of hydrogen between the protic solvent and the surface of the catalyst was fast relative to the rate of production of alkanes; consequently, the content of excess deuterium in the alkanes provided a measure of the rate of activation of the C–H bonds of the intermediate surface alkyls relative to the rate of their reductive elimination as alkanes. In deuterated alcohols (ROD), under conditions in which the rates of reduction were limited by mass transport of H_2 or D_2 to the catalyst surface (the mass-transport-limited regime, MTL; T = 40 °C, P_{H_2} = 0.17 atm), the alkanes contained deuterium atoms in excess of that required for stoichiometric reduction of the double bond; for example, the average isotopic content of cyclooctane from reduction of *cis*-cyclooctene in ethyl alcohol-*d* was $C_8H_4D_{12}$. Under conditions in which the rates of reduction were limited by the rate of a reaction occurring on the surface of the catalyst (the reaction-rate-limited regime, RRL; T = −20 °C, P_{H_2} = 2.4 atm), the extent of incorporation of excess deuterium was less than that observed under MTL conditions. A comparison of several deuterated alcohols ROD (R = methyl, ethyl, *n*-propyl, isopropyl, and *tert*-butyl) as deuterium donors in the reduction of *cis*-cyclooctene showed similar incorporation of deuterium into the cyclooctanes within each kinetic regime. The influence of acidity/basicity of the solvent on these reactions was small. The reductions of *cis*-cyclooctene under MTL conditions in D_2O/THF (1:1, v/v) where the pD of the D_2O was varied from 1 to 10 gave cyclooctanes with slightly more deuterium than analogous reductions in the deuterated alcohols; at pD 13, this trend was markedly reversed. Under MTL and RRL conditions, the rate of isotopic exchange of hydrogen between H_2O (D_2O) and the surface of the catalyst was slower at pH(D) 13 than in the range pH(D) 1–10.

Introduction

This paper describes the isotopic compositions of alkanes produced by the platinum-catalyzed reductions of olefins using H_2 (or D_2) in protic solvents, ROH(D) (eq 1; R = H(D) or alkyl).

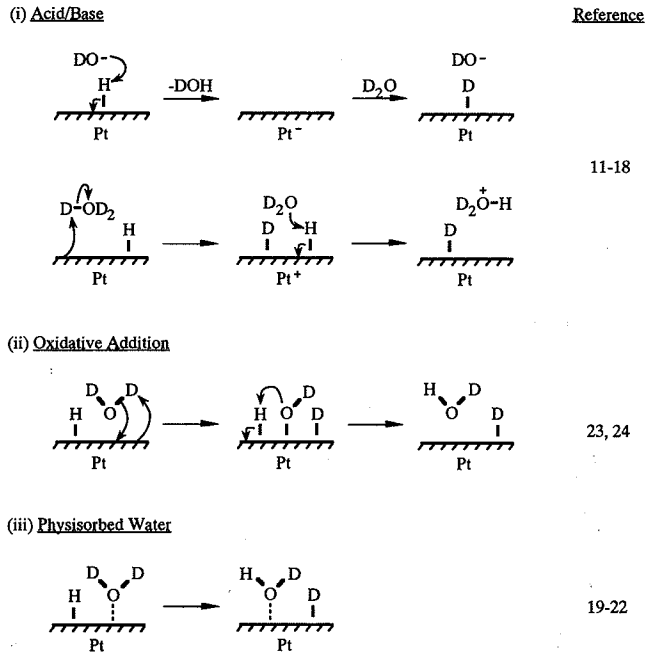
$$\text{olefin} + H_2(D_2) \xrightarrow[\text{Pt}]{\text{ROH(D)}} \text{alkane-}d_n \qquad (1)$$

This investigation is part of a larger project aimed at the synthesis and characterization of surface alkyls (R*) on platinum generated by the platinum-catalyzed reduction of (diolefin)dialkylplatinum(II) complexes ((DO)PtR_2) (eq 2).[2–7] In this reaction,



the surface alkyls result from the adsorption of the components of (DO)PtR_2 on the surface of the catalyst; they ultimately form alkanes by reaction with surface hydrides. These reductions generate, as intermediates, surface alkyls that initially have well-defined structures.[4] The rates of incorporation of deuterium into these surface alkyls can be examined relative to the rates of reductive elimination from the surface by measuring the amount of deuterium in the product alkanes.[5]

Scheme I. Possible Mechanisms of the Isotopic Exchange of H/D between Protic Solvents (ROD) and the Surface of Platinum



This system provides a new method for generating and studying surface alkyls on platinum. One complication exists: since surface alkyls derived from the R group and the diolefin are present on the catalyst at the same time, and since surface-catalyzed hydrogen interchange between these alkyls can be rapid,[5] disentangling the reactions involving the different organic groups present on the surface can be difficult. If, however, these reductions are performed in protic solvents, the contribution from isotopic exchange between the coadsorbed alkyls and diolefins to the overall isotopic composition of the alkane products can be reduced or eliminated by exchange between H(D)* and the solvent.[7]

In the heterogeneous platinum-catalyzed hydrogenations of olefins in protic solvents, the intermediate surface alkyls rapidly

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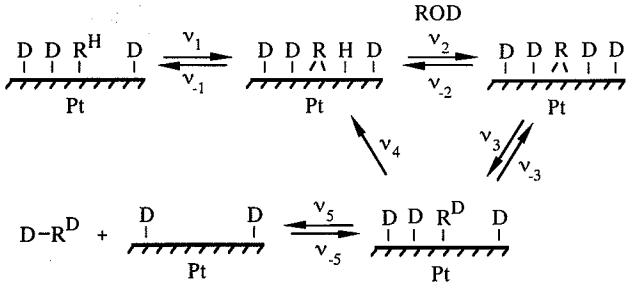
Scheme II. Proposed Mechanism for the Reduction of a Surface Alkyl on the Surface of Platinum in a Protic Solvent (ROD)



exchange isotopes of hydrogen with H(D)*, and the isotope from the solvent (RO*H* or RO*D*) is found in the product alkanes.[8-14] Incorporation of H/D from the solvent occurs via exchange between H(D)* and the hydroxy (deuteroxy) group of the solvent (eq 3). Although the mechanism of the exchange shown in eq 3 is not well understood, several mechanisms have been proposed and are summarized in Scheme I.

$$H^* + ROD \rightleftarrows D^* + ROH \qquad (3)$$

In one type of mechanism, the solvent (shown here, for simplicity, as D_2O) can either abstract a proton from a platinum surface bearing hydrogen, or donate a proton to this surface (i in Scheme I).[11-18] The reactions shown here might involve D_2O, D_3O^+, or OD^- as acids/bases. It is known, however, that isotopic exchange occurs between water *vapor* and hydrogen on the surface of platinum.[19-26] This observation indicates that acids and bases are not *required* for exchange (although they might still act as catalysts). Exchange between neutral water and surface hydrides on platinum might take place by a sequence involving oxidative addition of water to the surface and reductive elimination of water from the surface (ii in Scheme I).[21,22] Oxidative addition of this sort is common in heterogeneous catalysis (particulary when oxygen atoms are coadsorbed on the surfaces of metals)[27-36] and has support in homogeneous exchange reactions involving platinum(II).[37,38] Several kinetics studies have established a low energy of activation for exchange on platinum, and have shown no direct evidence for a species participating in reactions with surface hydrides that is dissociatively adsorbed.[19-22] The fact that surface hydrides on platinum and physisorbed water are kinetically identifiable intermediates (iii) does not preclude steps involving acid/base or oxidative addition of the type suggested by i and ii in Scheme I. We conclude that in these reactions, as with many elementary reactions, it has not yet been possible to provide a detailed mechanism based on classical kinetics.

Table I. Synthesis of the Various Isotopomers of Ethane

alkyl bromide	H^- or D^- [a]	ethanes-d_n
CH_3CH_2Br	H^-	d_0
$BrCH_2CH_2Br$	H^-	d_0
CH_3CH_2Br	D^-	d_1
CH_3CD_2Br	H^-	*1,1*-d_2
$BrCH_2CH_2Br$	D^-	*1,2*-d_2
CH_3CD_2Br	D^-	*1,1,1*-d_3
CD_3CH_2Br	H^-	*1,1,1*-d_3
CD_3CH_2Br	D^-	*1,1,1,2*-d_4
$BrCD_2CD_2Br$	H^-	*1,1,2,2*-d_4
CD_3CD_2Br	H^-	d_5
CD_3CD_2Br	D^-	d_6

[a] H^- denotes Super-hydride and D^- denotes Super-deuteride.

Scheme II provides a simple representation of the reactivity of a surface alkyl under our experimental conditions. We have identified reaction conditions under which the overall rate of reaction is limited by the mass transport of H_2 to the surface of the catalyst (mass-transport-limited conditions, MTL), or by a reaction occurring on the surface of the catalyst (reaction-rate-limited conditions, RRL).[3,7] Since the exchange of H/D between the surface of platinum and the protic solvent (step 2) is faster than the conversion of surface alkyls to alkanes, the excess deuterium found in the product alkanes provides a measure of the rate of exchange (and thus of the rate of C–H bond activation of the type shown in step 1) of the surface alkyls relative to the rate of their reductive elimination from the surface (step 5).

The work reported here had three objectives: (1) to characterize the exchange of H/D between the protic solvents and the surface of platinum (eq 3) using the reduction of simple olefins as a test system; (2) to establish the relative ability of ROD and D_2 to act as deuterium donors in the reduction of olefins; and (3) to determine the relative rates of exchange and reduction in kinetic regimes that were rate-limited by mass transport of H_2 to the surface of the catalyst (MTL regime), or by a reaction occurring on the surface of the catalyst (RRL regime). This paper does not attempt to describe the exact mode of bonding of the alkyl to the surface during the exchange process.

Our studies used platinum black as catalyst and 1,5-cyclooctadiene and *cis*-cyclooctene as substrates for reduction for several reasons. First, the reductions of olefins by H_2 over platinum are insensitive to the morphology of the surface of the catalyst.[39] Second, since platinum black is an unsupported catalyst, there are no issues concerning catalyst–support interactions or isotopic impurities originating in the support. Third, the mass spectrum of cyclooctane exhibits a clean parent ion (M^+) and is easily analyzed for isotopic composition. Fourth, cyclooctyl moieties on the surface of platinum rapidly undergo multiple exchange (Scheme II); thus, isotopic exchange phenomena can be readily

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Table II. Mass Spectral Data for Ethanes-d_n (n = 0–6)[a]

compd	m/z 28	29	30	31	32	33	34	35	36	relative sensitivity[b]	sets of ethanes[c] A	B
CH_3CH_3	100	21.2	22.7	0.5						1.1	A	B
CH_2DCH_3	60.0	100	22.6	27.0	0.5					0.96	A	B
CHD_2CH_3	38.8	100	80.2	22.2	28.3	0.7				0.69	A	
CH_2DCH_2D	43.9	87.8	100	23.7	31.6	0.1				0.59		B
CD_3CH_3	21.9	30.8	100	20.7	10.6	22.1	0.5			1.0	A	B
CD_3CH_2D	22.9	27.7	53.4	100	17.1	9.7	25.3	0.6		0.88	A	
CHD_2CHD_2	30.3	35.3	76.8	100	46.8	13.3	29.7	0.7		0.61		B
CD_3CHD_2	30.3	21.4	32.9	100	73.9	19.2	6.1	29.2	0.6	0.65	A	B
CD_3CD_3	18.0	0.0	26.5	0.0	100	1.0	14.1	0.0	19.1	1.1	A	B

[a] Values of m/z are the relative abundances of ions corrected for isotopic impurities due to hydrogen in the sources of deuterium. [b] The relative sensitivites multiplied by the relative abundances give the absolute intensities of ions produced from equimolar mixtures of the isotopomers of ethane. [c] The symbols A and B denote the individual sets of isotopomers used for the determination of the isotopic composition of ethanes.

observed. Finally, 1,5-cyclooctadiene is the diolefin coordinated to platinum in the majority of our studies of the reduction of $(DO)PtR_2$ complexes (eq 2).

Experimental Section

General Procedures. Solvents were deoxygenated by purging with argon; they were stored and transferred under argon. Methyl alcohol (99.9%, HPLC grade), isopropyl alcohol (anhydrous (anhyd) 99+%), *n*-propyl alcohol (anhyd, 99+%), *tert*-butyl alcohol (99.5+%, HPLC grade), THF (99.9%, HPLC grade), H_2O (HPLC grade), sulfuric acid (0.5 N in H_2O), sodium hydroxide (1 N in H_2O), methyl alcohol-*d* (99.5+ atom % D), ethyl alcohol-*d* (99.5+ atom % D), isopropyl alcohol-*d* (98+ atom % D), *tert*-butyl alcohol-*d* (98+ atom % D), deuterium oxide (99.8 atom % D), sulfuric acid-d_2 (98 wt % in D_2O, 99.5+ atom % D), sodium deuteroxide (30 wt % in D_2O, 99+ atom % D), lithium triethylborodeuteride (Super-deuteride, 1 M in THF, 95% D), lithium triethylborohydride (Super-hydride, 1 M in THF), bromoethane (98%), 1,2-dibromoethane (99%), dimethyl fumarate (97%), dimethyl 1,3-cyclohexadiene-1,4-dicarboxylate (90%), and platinum black (Lot nos. 10410HT and 03019KT) were purchased from Aldrich and used as received. We used CH_3CD_2Br (MSD, 99.5 atom % D), CD_3CH_2Br (MSD, 98 atom % D), CD_3CD_2Br (ICN Biomedicals, 98 atom % D), $BrCD_2CD_2Br$ (CIL, 98 atom % D), *n*-propyl alcohol-*d* (CIL, anhyd, 99% D), chloroform-*d* (MSD, 99.8% D), and ethyl alcohol (USI, absolute) without further purification. The substrates *cis*-cyclooctene (Wiley, 99.9%), 1,5-cyclooctadiene (Aldrich, 99+%), 1-methylcyclohexene (Aldrich, 97%), 1,2-dimethylcyclohexene (Wiley, 98%), dimethyl acetylenedicarboxylate (Aldrich, 99%), dimethyl maleate (Aldrich, 96%), and 1-methoxy-1,4-cyclohexadiene (Alfa) were passed through silica immediately prior to use. Dihydrogen and 10% dihydrogen in argon were the highest purity available from Matheson, and were passed through Ridox (Fisher Scientific) and activated molecular sieves before use. Ethylene and dideuterium were purchased from Matheson, and used as received. We prepared a 10% dideuterium in argon mixture for use in reductions under MTL conditions by evacuating an empty 10-L gas cylinder, filling it with 1 atm of dideuterium, and pressurizing it with argon to 150 psig.

We prepared authentic samples of ethane-d_0 through ethane-d_6 in order to deconvolute the mass spectral data for unknown mixtures of deuterated ethanes. We synthesized the ethanes by dissolving the appropriate ethyl bromide-d_n (~100 mg) in THF (1 mL) in a 10-mL round-bottomed flask equipped with a stir bar and a rubber septum, and adding by syringe a large excess (0.7 mL) of 1 M Super-hydride or Super-deuteride as indicated in Table I. Although the reaction appeared to be instantaneous, we allowed 0.5 h before sampling the headspace above the solution. The calculated distributions of the ethanes-d_n shown in Table II were corrected for isotopic impurities (<100 atom % D) originating in the ethyl bromides-d_n and/or the Super-deuteride.

We adjusted the pH of aqueous solutions (H_2O and D_2O) by adding aqueous sodium hydroxide or sulfuric acid to a known volume of water. In solutions of deuterium oxide, calculations were corrected for the higher density of deuterium-containing liquids.

We conducted the reactions in 20-mL pressure-bottle reactors (Lab Glass) silanized as described previously.[3] For reductions under RRL conditions, the neoprene septa (Lab Glass) used to cap the bottles were used as received; for reductions under MTL conditions, they were extracted with methylene chloride, and rinsed with ethyl alcohol before use. Reaction temperatures were maintained ±1 °C by immersing the reactors to within ~1 cm of their metal crown caps in mixtures of water/ethylene glycol (1:1, v/v) thermostated by a Neslab Cryocool (T < 0 °C) or a Fisher circulating bath (T > 0 °C). The low pressures of H_2 (or D_2) required for MTL conditions were obtained by using 10% H_2 (D_2) in argon mixtures. Dihydrogen (dideuterium) and 10% H_2 (D_2) in argon mixtures were admitted to the reactors through a syringe needle inserted into the septum. Pressures inside the reactors were measured by inserting a syringe needle equipped with a pressure gauge through the septum of the reactor, and are probably accurate to ±5% absolute. Since the headspace of the reactors did not permit enough H_2 (or D_2) for complete reduction of substrate under MTL conditions, these reductions were run with a slow leak (~5 mL/min of gas) to provide a constant pressure of H_2 (or D_2) over the solution. The slow leak was regulated by a fine-metering valve (Nupro) connected to a syringe needle inserted through the septum of the reactor.

Methods. In a previous paper,[3] we rigorously defined MTL and RRL regimes for the reductions of (1,5-cyclooctadiene)dimethylplatinum(II) ((COD)PtMe$_2$, **1**) in *n*-heptane. Equations 4 and 5 summarize the rate

$$\text{MTL} \quad -d\mathbf{1}/dt = 0.086 \pm 0.012\ (\mu\text{mol s}^{-1}\ \text{atm}^{-1.05}) \times (1.0 + (2.3 \times 10^{-5})\omega + (5.5 \times 10^{-7})\omega^2) S_{Pt}^{0.0\pm0.2} P_{H_2}^{1.05\pm0.07} [\mathbf{1}]^{0.0\pm0.2} \quad (4)$$

$$\text{RRL} \quad -d\mathbf{1}/dt = 0.014 \pm 0.003\ (\mu\text{mol s}^{-1}\ \text{atm}^{-0.38}(\mu\text{g·atom})^{-1.2}) \omega^{0.0\pm0.3} S_{Pt}^{1.2\pm0.2} P_{H_2}^{0.38\pm0.04} [\mathbf{1}]^{0.0\pm0.2} \quad (5)$$

laws we obtained; ω is the rate of rotation of a magnetic stir bar, S_{Pt} is the surface area of platinum (determined by H_2/O_2 titration[3,7]), and P_{H_2} is the pressure of dihydrogen. In the accompanying paper,[7] we show that the experimental conditions used in *n*-heptane also generate MTL and RRL regimes for reductions in ethyl alcohol. Since the conditions required to generate MTL and RRL regimes in *n*-heptane and ethyl alcohol—two solvents with very different character—are the same, we have assumed that these conditions also generate MTL and RRL regimes in the other solvents surveyed here. In the present study, MTL conditions were as follows: T = 40 °C, P_{H_2} = 0.17 atm, ω = 1800 rpm, S_{Pt} = 20 μg·atom (40 mg of Pt black), 3 mL of solvent, and ~15 mg of olefin or diolefin. RRL conditions were as follows (except when water/THF (1:1, v/v) was the solvent): T = −20 °C, P_{H_2} = 2.4 atm, ω = 1800 rpm, S_{Pt} = 15 μg·atom (30 mg Pt black), 3 mL of solvent, and ~15 mg of olefin; for reductions in water/THF, all variables were the same except temperature (T = 10 °C) and pressure (P_{H_2} = 3.0 atm).

A typical reduction was performed in the following manner. A reaction vessel equipped with a football-shaped magnetic stir bar (10 × 6 mm) was charged with catalyst, capped, purged for ~10 min with Ar, and placed in the constant-temperature bath. Solvent (1 mL) was added to the catalyst, and stirring was begun. The vessel was purged with H_2 (or D_2) for 30 s, and then held at constant pressure of H_2 (or D_2) for 10 min. Stirring was stopped; the catalyst was allowed to settle to the bottom of the reactor, and the solvent was removed via cannula. The substrate, dissolved in 3 mL of solvent, was added through a cannula under a pressure of H_2 (or D_2),[40] and stirring was resumed. Reductions under MTL conditions were stopped after 30 min; reductions under RRL conditions were stopped after 1 h. In general, conversion of olefin to alkane was complete in the allotted times, unless noted otherwise.

Isotopic Analysis. We used a Hewlett-Packard 5992A GC/MS (70-eV electron-impact ionization) to measure mass spectra. Ethanes were analyzed with use of a 2-m Apiezon column operated at 30 °C; all other hydrocarbons were analyzed with use of a 2-m 5% SE-30 column. We collected the data using the software for Selected Ion Monitoring from Hewlett-Packard.

Ethanes-d_n. Table II summarizes the relevant mass spectra of the ethanes-d_n obtained with our mass spectrometer. The absolute intensities of ions produced from equimolar mixtures of isotopomers of ethane can

(40) In the reductions of ethylene, we added 3 mL of solvent and then added 1 mL (at 1 atm) of ethylene by gas-tight syringe.

Table III. Isotopic Compositions of the Ethanes Generated by the Addition of Super-Hydride or Super-Deuteride to Known Mixtures of Ethyl Bromides-d_n

mixtures of ethyl bromides-d_n	H^- or D^- [a]	calcd/found[b]	ethanes-d_n d_0	d_1	d_2	d_3	d_4	d_5	d_6
(a) $CH_3CH_2Br + CH_3CD_2Br$	H^-	C	50.0	0.5	49.5				
		F	49.2	1.7	49.2				
(b) $CH_3CH_2Br + CH_3CD_2Br$	D^-	C	2.3	48.2	0.2	4.8	44.4		
		F	1.3	50.9		3.5	44.9		
(c) $CH_3CH_2Br + CD_3CD_2Br$	H^-	C	50.1			0.2	4.6	45.1	
		F	51.2	0.6		0.3	3.1	45.6	
(d) $CH_3CH_2Br + CD_3CD_2Br$	D^-	C	2.3	48.1			0.4	6.5	42.7
		F	2.1	47.9	1.3			6.2	44.3

[a] H^- denotes Super-hydride and D^- denotes Super-deuteride. [b] The letter C denotes the calculated distributions, and F denotes the distributions found by analysis.

Table IV. Mass Spectral Data for Cyclooctane, Methylcyclohexane, 1,2-Dimethylcyclohexane, and Methoxycyclohexane

compd	range of m/z analyzed	$(M + 1)^+$ [a]	$(M - 1)^+$ [a]	$(M - x)^+$ [b]	$(M - y)^+$ [c]
cyclooctane	112–128	8.8	<1.0	97 (16%)	84 (54%)
methylcyclohexane	98–112	7.4	5.1	84 (11%)	83 (176%)
1,2-dimethylcyclohexane	112–128	8.7	2.9	98 (17%)	97 (217%)
methoxycyclohexane	114–128	7.8	4.9	85 (64%)	83 (13%)

[a] These values are the percent ionic abundances relative to M^+. [b] These values are m/z for the fragment ion (>1% abundance relative to M^+) of highest mass less than $m/z = (M - 1)^+$. The values in parentheses are ionic abundances relative to M^+. [c] These values represent m/z for the fragment ion (>1% abundance relative to M^+) of highest mass less than $m/z = (M - x)^+$. The values in parentheses are ionic abundances relative to M^+.

be calculated by multiplying the relative abundances by the relative sensitivities. For set A, we determined the sensitivities of ethanes-d_n (n = 0–2, 4–6) relative to ethane-d_3 by generating ~1:1 mixtures of ethane-d_3 and ethanes-d_n of known composition and analyzing them using the singular-value decomposition method described previously.[4,5] Set B differs from set A only in the position of the deuterium atoms in the d_2- and d_4-isotopomers of ethane.[41] For set B, we determined the sensitivity of ethane-*1,2*-d_2 relative to ethane-d_6 and the sensitivity of ethane-*1,1,2,2*-d_4 relative to ethane-d_0. Ethanes from reductions of ethylene were analyzed with use of both basis sets; the values of d_{av} from these different analyses agreed to within ±5% relative.

We tested the accuracy of our isotopic analyses of ethanes by generating independent mixtures of ethanes-d_n of known composition. The results of these analyses, given in Table III, demonstrate that the distributions of ethanes-d_n can be known to ±2% absolute. Taking a conservative approach to these data, we claim that the distributions of ethanes-d_n from reductions of ethylene are accurate to ±5% absolute.

Cyclooctanes-d_n, Methylcyclohexanes-d_n, 1,2-Dimethylcyclohexanes-d_n, and Methoxycyclohexanes-d_n. Table IV gives the relevant mass spectral data for cyclooctane-d_0, methylcyclohexane-d_0, 1,2-dimethylcyclohexane-d_0, and methoxycyclohexane-d_0. All distributions of ions obtained from the mass spectral analyses of the products from reductions were corrected for natural abundance of ^{13}C by iteratively subtracting from the nth peak the $(M + 1)^+$ percentage (from Table IV) of the corrected value for the $(n - 1)$th peak, and normalizing the resulting distribution. We made no corrections for $(M - 1)^+$ abundances. In analyses of cyclooctanes-d_n, the $(M - 15)^+$ fragment ions from m/z = 127 and 128 probably do not contribute to m/z = 112 and 113, respectively, since the parent ions are highly deuterated. As a consequence, we did not correct for the $(M - 15)^+$ fragment ions in our analyses. Similarly, in analyses of methylcyclohexanes-d_n, m/z = 112 probably does not contribute to m/z = 98 $(M - 14)^+$; thus, no correction for $(M - 14)^+$ was performed. We observed no incorporation of deuterium higher than d_{10} in analyses of 1,2-dimethylcyclohexanes-d_n. The $(M - 14)^+$ and $(M - 15)^+$ fragment ions therefore had no contribution to the observed distributions, and no corrections were necessary. Other fragment ions from the alkanes did not fall within the range of relevant m/z; therefore, no further corrections were made.

(41) The only isotopomer of ethane not synthesized and therefore not part of either set was CD_2HCDH_2.

Dimethyl Succinates-d_n and Dimethyl Cyclohexanedicarboxylates-d_n. The content of deuterium in the dimethyl succinates and the dimethyl cyclohexanedicarboxylates was determined by integration of the ^1H NMR spectra using the methoxy groups as internal standards, and assumed no isotopic exchange of the methoxy hydrogens. We recorded NMR spectra in $CDCl_3$ on a Bruker AM 300 spectrometer with a relaxation delay of 15 s for accurate integrations. Chemical shifts (δ) are reported relative to $CHCl_3$ at δ 7.24. For analyses of dimethyl cyclohexanedicarboxylates, we integrated the hydrogens in the cyclohexyl ring (δ 1.3–2.6) relative to those in the methoxy groups (δ 3.66).

For analyses of dimethyl succinates, we integrated the methylene hydrogens (δ 2.61) relative to the methoxy hydrogens (δ 3.68). Reductions under MTL conditions in ethanol produced small amounts (typically <10%) of the mixed ester (methyl ethyl succinate). In these cases, we added the area of the methyl hydrogens in the ethoxy group (δ 0.9) to the area of the methoxy hydrogens, and determined d_{av} by comparing the combined area to that from the methylene signal. We believe that all values of d_{av} obtained from analyses by ^1H NMR are good to ±5% absolute.

Results

Reductions of Olefins in Ethyl Alcohol under MTL Conditions. We use the average content of deuterium, d_{av} (eq 5), to describe the amount of deuterium in the product alkanes. The reductions

$$d_{av} = \sum_{n=1}^{m} n(\%\ \text{alkane-}d_n) \qquad (6)$$

of *cis*-cyclooctene with D_2 in ethyl alcohol-*d* (EtOD) under MTL conditions incorporated, on average, more than twelve deuterium atoms into the cyclooctanes (Table V). When cyclooctane-d_0 was subjected to these conditions, no deuterium was incorporated; therefore, we believe that the incorporation of deuterium occurs exclusively prior to reductive elimination of from the surface. Figure 1 shows that, under MTL conditions, the incorporation of deuterium was not significantly decreased by the use of H_2/EtOD instead of D_2/EtOD, and that reductions using D_2/EtOH produced cyclooctanes containing almost no deuterium.

Under MTL conditions, the reductions of 1,5-cyclooctadiene (COD) and *cis*-cyclooctene produced similarly deuterated cyclooctanes. The magnitude and similarity of the values of d_{av} reflect the greater reactivity (i.e., the faster rate of C–H bond activation relative to the rate of reductive elimination) of cyclooctyl moieties on the surface of platinum than of the surface moieties generated from the other substrates in Figure 1 and Table V.

The reductions of 1-methylcyclohexene under MTL conditions using both D_2/EtOD and H_2/EtOD resulted in an average incorporation of three deuterium atoms in excess of the two required for stoichiometric reduction of the double bond. Similarly, the reductions of 1,2-dimethylcyclohexene incorporated an average of two excess deuteriums. The extent of incorporation of deuterium in the reductions of both of these substrates using D_2/EtOH was small.

The reduction of ethylene under MTL conditions using D_2/EtOD and H_2/EtOD produced peaks in the distribution of ethanes-d_n at ethane-d_2 and ethane-d_6. Kita and co-workers reported a similar distribution in the deuteration of ethylene in aqueous solution under related MTL conditions;[12] they also found peaks in the distributions of alkanes-d_n at alkane-d_2 and perdeuteration in reductions under MTL conditions of propylene, butenes, and

Table V. Isotopic Compositions (d_{av}) of the Alkanes from the Reductions of the Corresponding Olefins in Ethyl Alcohol[a]

alkene	MTL			RRL		
	D_2/EtOD	H_2/EtOD	D_2/EtOH	D_2/EtOD	H_2/EtOD	D_2/EtOH
cis-cyclooctene	12.2 ± 0.2	11.9 ± 0.1	0.08 ± 0.01	4.1 ± 0.1	2.7 ± 0.0	0.25 ± 0.08
1,5-cyclooctadiene	13.2 ± 0.2	12.6 ± 0.2	0.44 ± 0.02	5.7 ± 0.0	4.5 ± 1.6	0.23 ± 0.03
1-methylcyclohexene	5.4 ± 0.4	4.6 ± 0.7	0.02 ± 0.01	2.3 ± 0.0	2.1 ± 0.1	0.01 ± 0.00
1,2-dimethylcyclohexene						
cis[b]	4.0 ± 0.1	3.7 ± 0.0	0.04 ± 0.03	3.1 ± 0.1	2.9 ± 0.0	0.03 ± 0.01
trans[b]	3.9 ± 0.0	3.7 ± 0.0	0.05 ± 0.04	3.4 ± 0.0	3.1 ± 0.0	0.03 ± 0.01
ethylene	4.2 ± 0.3	4.1 ± 0.1	0.5 ± 0.1	1.9 ± 0.0	1.3 ± 0.3	0.63 ± 0.02

[a] The value indicated by ± is the difference between duplicate runs. [b] The reduction of 1,2-dimethylcyclohexene yielded 60% *cis*- and 40% *trans*-dimethylcyclohexanes under MTL conditions, and 80% *cis*- and 20% *trans*-dimethylcyclohexanes under RRL conditions.

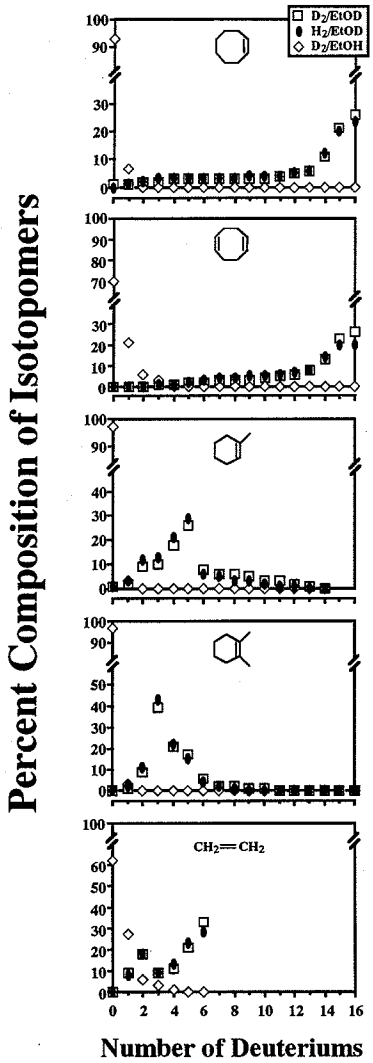

Figure 1. Percent composition of the isotopomers as a function of the number of deuterium atoms in the alkanes-d_n from the reductions of *cis*-cyclooctene, 1,5-cyclooctadiene, 1-methylcyclohexene, 1,2-dimethylcyclohexene, and ethylene in ethyl alcohol under MTL conditions.

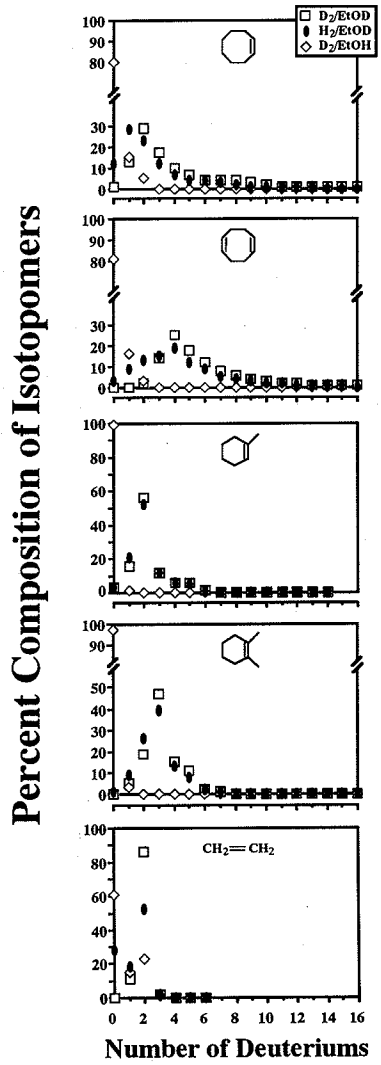

Figure 2. Percent composition of the isotopomers as a function of the number of deuterium atoms in the alkanes-d_n from the reductions of *cis*-cyclooctene, 1,5-cyclooctadiene, 1-methylcyclohexene, 1,2-dimethylcyclohexene, and ethylene in ethyl alcohol under RRL conditions.

2-butyne.[14,42-45] Here, the reduction of ethylene using D_2/EtOH produced 27% ethane-d_1; this reduction and that of COD were the only ones to show significant incorporation of deuterium using D_2/EtOH under MTL conditions.

Reductions of Olefins in Ethyl Alcohol under RRL Conditions. The reductions of olefins under RRL conditions produced alkanes containing substantially less deuterium than did reductions under MTL conditions (Table V and Figure 2). Nevertheless, some of the basic trends observed for reductions under MTL conditions were also observed for reductions under RRL conditions: H_2/EtOD and D_2/EtOD gave similar values of d_{av}, and reductions with D_2/EtOH resulted in little or no incorporation of deuterium.

Structure of the Deuterium Donor. To explore the isotopic exchange of hydrogen between the protic solvent and the surface of the catalyst, and to define the role of the solvent in influencing the extent of incorporation of deuterium into the surface alkyls, we studied a variety of reductions of *cis*-cyclooctene under both MTL and RRL conditions. In one series of experiments (Table VI), we varied only the structure of R in ROH(D): R = methyl, ethyl, *n*-propyl, isopropyl, and *tert*-butyl. Reductions using D_2/ROD, H_2/ROD, and D_2/ROH showed that the content of

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(43) Kita, H.; Shimazu, K.; Kakuno, Y.; Katayama-Aramata, A. *J. Catal.* **1982**, *74*, 323–331.
(44) Katsuaki, S.; Kita, H. *J. Catal.* **1984**, *86*, 129–136.
(45) Kita, H.; Nakajima, H. *J. Chem. Soc., Faraday Trans 1* **1981**, *77*, 2105–2114.

Table VI. Isotopic Compositions (d_{av}) of the cyclooctanes from the Reductions of *cis*-Cyclooctene in Alcoholic Solvents[a]

	MTL			RRL		
alcohol	D_2/ROD	H_2/ROD	D_2/ROH	D_2/ROD	H_2/ROD	D_2/ROH
methyl	10.7 ± 0.0	10.8 ± 0.5	0.42 ± 0.00	3.7 ± 0.0	3.5 ± 0.0	0.08 ± 0.00
ethyl	12.2 ± 0.2	11.9 ± 0.2	0.08 ± 0.01	4.1 ± 0.1	2.7 ± 0.0	0.25 ± 0.07
n-propyl	11.9 ± 0.4	11.8 ± 0.3	0.13 ± 0.05	3.0 ± 0.0	2.7 ± 0.6	0.2 ± 0.1
isopropyl	11.5 ± 0.2	11.5 ± 0.2	0.10 ± 0.01	3.9 ± 0.2	3.5 ± 0.7	0.3 ± 0.2
tert-butyl[b]	10.7 ± 0.2	11.2 ± 0.3	0.13 ± 0.01			

[a] The value indicated by ± is the difference between duplicate runs. [b] We were unable to perform the reductions in *tert*-butyl alcohol under RRL conditions (−20 °C) because this solvent freezes at 25 °C.

Table VII. Isotopic Compositions (d_{av}) of the cyclooctanes from the Reductions of *cis*-Cyclooctene in Water/THF (1:1, v/v) in the range pH(D) 1–13[a]

	MTL						RRL		
pH	D_2/D_2O	% conv[b]	H_2/D_2O	% conv[b]	D_2/H_2O	% conv[b]	D_2/D_2O	H_2/D_2O	D_2/H_2O
1	14.0 ± 0.4	90	13.8 ± 0.1	66	0.09 ± 0.04	100	7.7 ± 0.1	8.1 ± 0.1	0.07 ± 0.01
4	13.8 ± 0.2	82	13.0 ± 0.3	65	0.20 ± 0.03	100	8.0 ± 0.2	7.9 ± 0.1	0.26 ± 0.01
7	13.1 ± 0.3	61	13.0 ± 0.4	83	0.10 ± 0.03	100	7.1 ± 0.0	6.4 ± 0.5	0.17 ± 0.01
10	13.6 ± 0.2	93	12.6 ± 0.2	53	0.17 ± 0.05	100	7.8 ± 0.1	7.4 ± 0.0	0.14 ± 0.02
13	5.8 ± 0.1	62	4.0 ± 0.0	42	0.8 ± 0.7	91	4.7 ± 0.7[c]	1.3 ± 0.4[c]	1.2 ± 0.7[c]

[a] The value indicated by ± is the difference between duplicate runs. To avoid freezing the solvent, reductions under RRL conditions were performed at 10 °C rather than −20 °C. [b] These values represent the percent conversion to cyclooctanes after 30 min of reaction. [c] Percent conversions after 1 h at pH 13 were 82, 90, and 91% for D_2/D_2O, H_2/D_2O, and D_2/H_2O, respectively. All other conversions under RRL conditions were 100%.

deuterium in the cyclooctanes was not substantially different for any of the alcohols studied; the values of d_{av} under a given set of reaction conditions (e.g., MTL, D_2/ROD) are probably indistinguishable within experimental error when small differences in the isotopic purity of the ROD are considered. This study indicates that the alcohols do not differ substantially in their ability to exchange with H(D)*.

In a second study (Table VII), we varied the pH(D) of water in 1:1 (v/v) mixtures of THF and H_2O (or D_2O). In these solvent systems, reductions in the RRL regime were conducted at 10 °C rather than at −20 °C to avoid freezing the solvent; these results, therefore, probably represent reactions predominantly under RRL control, but with some contribution from mass-transport limitation. Four features of these data are interesting. First, in both kinetic regimes, there were no significant differences in isotopic incorporation over a range of values of pH(D) between 1 and 10; at pH(D) 13, however, less deuterium was incorporated from the deuterated solvent than at other values of pH(D). Second, several of these reductions did not go to completion in the allotted times; the reductions in water/THF were apparently slower than in alcohols. Third, the content of deuterium in the cyclooctanes from reductions under MTL conditions in D_2O/THF was higher than in deuterated alcohols (d_{av} = 14.0 for D_2 + D_2O/THF and d_{av} = 11.4 as an average for all D_2 + ROD); an analogous comparison under RRL conditions is not possible since the RRL conditions used for reductions were different in the alcohols and in the water/THF system. Fourth, at pH(D) 13 the isotope present in the gas (H_2 or D_2) contributed substantially to the isotopic content of the cyclooctanes; in contrast, at pH(D) 1–10 (as in alcoholic solvents) the isotope in the protic solvent dictated the isotopic composition of the cyclooctanes.

The observation that the incorporation of deuterium under MTL conditions was greater in D_2O/THF than in deuterated alcohols deserves further comment. For both systems of solvents, we infer that the fraction of deuterium atoms on the surface ($F_D = D^*/(D^* + H^*)$) is similar in reductions with D_2/ROD and H_2/ROD, and that $F_D \approx 0$ for both systems in reductions with D_2/ROH; thus, the isotopic exchange of surface hydrides with water/THF and alcohols appears equally facile. Since the reductions of olefins permits the observation of relative rates of exchange and reduction, the origin of the greater incorporation of deuterium for reductions in the aqueous system than in the alcohols is due either to a faster rate of C–H bond activation, or to a slower rate of reduction (reductive elimination as alkane) in the aqueous system than in the alcohols. Although we did not measure absolute rates of reduction, the reductions in water/THF appear to be slower than those in alcohols: conversion to alkane was not complete after 0.5 h in water/THF; conversion was complete within this time in the alcohols. A slower rate of reduction in water/THF probably increases the residence time of the cyclooctyl moieties on the surface of the catalyst and permits greater isotopic exchange before reductive elimination as cyclooctanes-d_n. We do not, however, rule out poisoning of the catalyst during the reductions in the aqueous system.

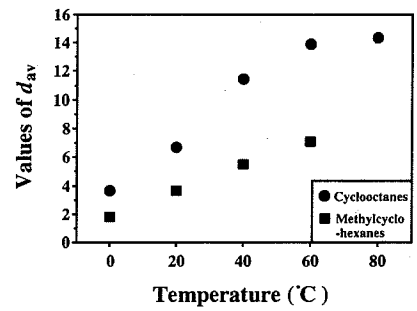

Figure 3. Values of d_{av} as a function of temperature for the alkanes-d_n from the reductions of *cis*-cyclooctene and 1-methylcyclohexene in D_2O/1,4-dioxane (1:1, v/v) under MTL conditions.

Table VIII. Isotopic Compositions (d_{av}) of the Alkanes from the Reductions under MTL Conditions[a] of *cis*-Cyclooctene and 1-Methylcyclohexene by H_2 in D_2O/1,4-Dioxane (1:1, v/v) at Several Temperatures[b]

temp (°C)	cyclooctanes	% conv[c]	methyl-cyclohexanes	% conv[c]
0	3.6 ± 0.2	53	1.8 ± 0.0	62
20	6.7 ± 1.6	51	3.6 ± 0.4	69
40	11.4 ± 0.5	66	5.5 ± 0.0	67
60	13.9 ± 0.3	78	7.1 ± 0.4	60
80	14.4 ± 0.6	98	*d*	

[a] Mass-transport limitation of the rate of reaction was not confirmed at temperatures other than 40 °C. [b] The value indicated by ± is the difference between duplicate runs. [c] These values represent the average percent conversion of olefin to alkane after 30 min of reaction. [d] The reduction of 1-methylcyclohexene at 80 °C produced quantities of methylcyclohexane that were too small for accurate analysis by GC/MS.[46]

Effect of Temperature on the Incorporation of Deuterium in Reductions of *cis*-Cyclooctene and 1-Methylcyclohexene in the MTL Regime. Figure 3 and Table VIII summarize the values of d_{av} as a function of temperature for the reductions of two representative substrates having relatively high and low propensity for incorporation of deuterium: *cis*-cyclooctene and 1-methyl-

Table IX. Isotopic Compositions (d_{av}) of the Dimethyl Succinates from the Reductions of Dimethyl Fumarate, Dimethyl Maleate, and Dimethyl Acetylenedicarboxylate, of the Dimethylcyclohexane-1,4-dicarboxylates from Dimethyl 1,3-Cyclohexadiene-1,4-dicarboxylate, and of the Methoxycyclohexanes from 1-Methoxy-1,4-cyclohexadiene in Protic Solvents under MTL Conditions[a]

substrate	MTL			RRL		
	D_2/EtOD	H_2/EtOD	D_2/EtOH	D_2/EtOD	H_2/EtOD	D_2/EtOH
dimethyl fumarate	2.1 ± 0.1	1.8 ± 0.0	0.00 ± 0.05	2.1 ± 0.1	1.7 ± 0.1	0.02 ± 0.02
dimethyl maleate	1.7 ± 0.1	1.7 ± 0.0	0.00 ± 0.02	2.0 ± 0.0	1.7 ± 0.1	0.03 ± 0.02
dimethyl acetylenedicarboxylate	3.9 ± 0.0	3.8 ± 0.0	0.44 ± 0.04	3.9 ± 0.1	3.2 ± 0.0	0.5 ± 0.2
1-methoxy-1,4-cyclohexadiene		6.2 ± 0.1[b]				
dimethyl 1,3-cyclohexadiene-1,4-dicarboxylate		5.3 ± 0.0[c]				

[a] The value indicated by ± is the difference between duplicate runs. [b] These reductions were performed at 60 °C rather than 40 °C. [c] These reductions were performed in MeOD at 50 °C rather than in EtOD at 40 °C.

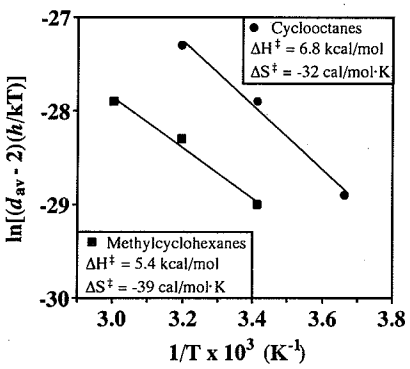

Figure 4. Plot of ln $[(d_{av} - 2)(h/kT)]$ vs $1/T$ for the reductions of *cis*-cyclooctene and 1-methylcyclohexene.

cyclohexene, respectively.[46] These reductions were conducted in D_2O/1,4-dioxane (1:1, v/v) in the MTL regime; we used 1,4-dioxane rather than THF in order to cover a larger temperature range; we used the MTL regime rather than the RRL regime in order to maximize isotopic exchange. The data highlight several features of the reaction. First the extent of incorporation of deuterium increased as the temperature was increased in the reductions of both substrates. Second, the slope was greater for the cyclooctanes than for the methylcyclohexanes in the plots of values of d_{av} vs temperature. Third, values of d_{av} for the cyclooctanes begin to asymptotically approach d_{16} at approximately 60 °C.

A plot of ln $[(d_{av} - 2)(h/kT)]$ vs $1/T$ gives observed values of $\Delta G^{\ddagger}$ at room temperature for isotopic exchange of cyclooctyl* moieties (16 kcal/mol) and methylcyclohexyl* moieties (17 kcal/mol) with values of $\Delta G^{\ddagger}$ increasing more rapidly with temperature for methylcyclohexyl* than for cyclooctyl* (Figure 4). These values are described by eq 7, which shows that values of

$$\Delta G^{\ddagger}_{obsd} = \Delta G^{\ddagger}_{exch} - \Delta G^{\ddagger}_{reduc\ elimin} \quad (7)$$

$\Delta G^{\ddagger}_{obsd}$ represent lower limits on $\Delta G^{\ddagger}_{exch}$ (and thus lower limits on $\Delta G^{\ddagger}$ for C–H bond activation of surface alkyls).[47] Values of $\Delta H^{\ddagger}_{reduc\ elimin}$ are probably similar for all substrates under these conditions, and are also probably small (<3 kcal/mol).[3] In contrast, values of $\Delta S^{\ddagger}_{reduc\ elimin}$, although strongly influenced by mass transport of H_2 (or D_2) to the surface of the catalyst, are probably different from substrate to substrate. As a consequence, we cannot infer directly values of $\Delta G^{\ddagger}_{exch}$.

Applications to the Synthesis of Isotopically Enriched Compounds. Our studies of the reductions of olefins in protic solvents revealed several strategies that are potentially useful in the synthesis of isotopically labeled compounds. First, the ability to incorporate deuterium into organic compounds by metal-catalyzed reduction of olefins using H_2 and D_2O or deuterated alcohols does not require expensive D_2. The extent of incorporation using ROD is essentially independent of the isotopic composition of the hydrogen (deuterium) gas; consequently, there is no isotopic penalty to pay in using H_2 instead of D_2. Second, the technique should be applicable to the synthesis of tritiated compounds. Third, the opportunity to achieve multiple exchanges of hydrogen for deuterium (or tritium) should receive wide application. Fourth, if maximum incorporation of deuterium (or tritium) is desired, the reductions should be carried out under MTL conditions rather than RRL conditions. Fifth, for the reduction of molecules having functional groups that are easily hydrolyzed, the pH may be varied over a wide range to minimize this side reaction. Sixth, the reduction of molecules that are sensitive to transesterification can utilize a variety of alcoholic solvents either to effect or to prevent transesterification. We surveyed several reductions illustrating these opportunities (Table IX).

Conclusions

(1) The isotopic exchange of hydrogen between protic solvents and the surface of the catalyst is faster than reductive elimination of R* as alkane. Under both MTL and RRL conditions, the isotope found in the alkanes formed by the reductions of olefins in protic media originates predominantly from the OH(D) group of the solvent rather than from the reductant (H_2 or D_2).[48] The fraction of deuterium atoms on the surface of the catalyst ($F_D = D^*/(D^* + H^*)$) is similar for reductions in D_2/ROD and H_2/ROD and is ~0 for reductions in D_2/ROH; in qualitative terms, the rate of isotopic exchange of hydrogen between the catalyst surface and the protic solvent is fast relative to the rate of production of alkane. With the exception of a previous communication from our group,[49] the high efficiency of isotopic exchange of hydrogen between the protic solvent and the surface of platinum is, to our knowledge, previously undocumented.[50,51]

(46) The reduction of 1-methylcyclohexene at 80 °C gave inconsistent results; the quantities of methylcyclohexane produced were too small for accurate analysis by GC/MS. This situation probably resulted because of the relatively high volatility of this substrate, and the use of a slow leak in our experimental design.

(47) The values of $\Delta G^{\ddagger}_{exch}$ are themselves lower limits on $\Delta G^{\ddagger}$ for C–H bond activation for two reasons: (1) the activation of C–D bonds (which probably occurs to a greater extent at higher temperatures) is not reflected in values of d_{av} and (2) the exchange of H* (generated by loss from surface alkyls) with ROD to form D* is close to but probably less than 100% efficient; therefore, a small fraction of H* moieties are probably reincorporated into the surface alkyls.

(48) In several of our systems, it appears that ROH exchanges more efficiently with the H(D)* pool than does ROD, particularly under RRL conditions. The most compelling example is the reduction of *cis*-cyclooctene under RRL conditions in ethyl alcohol (Table V), where $d_{av}(D_2/EtOD) > d_{av}(H_2/EtOD) + d_{av}(D_2/EtOH)$. Since we do not see this trend in all cases, we do not believe an isotope effect causes the differences; perhaps the exchange reaction is particularly sensitive under RRL conditions to minor impurities in the solvent.

(49) Lee, T. R.; Whitesides, G. M. *J. Am. Chem. Soc.* **1991**, *113*, 369–370.

(50) The data in ref 8–14 support our contention.

(51) Two reports argue that the efficiency of exchange varies with reaction conditions: those in which the rate of reaction is governed by diffusion of H_2 to the surface of the catalyst (as in our MTL regime) vs those in which the rate of reaction is governed by diffusion of olefin to the surface of the catalyst (i.e., a different type of mass-transport limitation).[13,14] These studies suggest that under MTL conditions similar to those reported here, the rate of isotopic exchange between H(D)* and ROD(H) is of the same order of magnitude as the rate of reduction, but under conditions where diffusion of olefin to the surface is rate-limiting, the rate of isotopic exchange is faster than the rate of reduction. Other reports contend that the rate of isotopic exchange is negligible compared to the rate of reduction.[52,53] These discrepencies probably result from the use of different platinum catalysts in each of the studies.

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(2) The mechanism of the isotopic exchange probably does not involve dissociation of a surface hydride (deuteride) from the surface as a proton (deuteron). The mechanism of the isotopic exchange of hydrogen between protic solvents and a platinum surface remains ill-defined. If the exchange proceeds by dissociation ($H^* \rightarrow H^+$), then the rate of exchange should be faster at high pH(D) and slower at low pH(D). Our system is sensitive to the *relative* rates of exchange between the solvent and H(D)*, and of incorporation of H(D)* into R*; consequently, if, at all values of pH(D), the rate of dissociation were much faster than the rate of exchange, we would not detect any variation in the rate of exchange as a function of pH(D). In the range of pD 1–10, we observe no significant differences in the values of d_{av} between reductions of *cis*-cyclooctene using H_2 and D_2 in D_2O/THF; reductions using D_2 in H_2O/THF give $d_{av} \approx 0$. At pD 13, however, under MTL and RRL conditions the values of d_{av} are lower for the reductions using H_2 in D_2O/THF than those using D_2 in D_2O/THF, and at pH 13, the reductions using D_2 in H_2O/THF give $d_{av} > 0$. These results indicate that the relative rates of isotopic exchange and formation of alkane do not vary markedly with pH(D) except at high pH(D): the rate of isotopic exchange (relative to the rate of production of alkane) is *slower* at pH(D) 13 than at pH(D) 1–10.[54]

Since the rate of isotopic exchange of hydrogen between the platinum surface and protic solvents (relative to the rate of production of alkane) is slowest at high pH, our data are not consistent with the mechanism of dissociation of H* into solution as H^+ (mechanism i in Scheme II). Unfortunately, we cannot distinguish between the associative mechanisms.

(3) The rapid isotopic exchange between ROH(D) and H(D)* provides a measure of the rate of C–H bond activation of surface alkyls relative to the rate of their reductive elimination as alkanes. Isotopic exchange between H(D)* and ROH(D) is fast when H(D)* originates from H_2 (or D_2). The exchange is also fast when the H(D)* is derived from a surface alkyl by C–H bond activation. For example, the reduction under MTL conditions of 1,5-cyclooctadiene with D_2 in ethyl alcohol-*d* gave $d_{av} = 13.2$ (Table V), while the reduction under MTL conditions of 1,5-cyclooctadiene with D_2 in *n*-heptane gave $d_{av} = 4.4$.[4] The difference between solvents having and lacking exchangeable deuterons strongly supports *rapid* exchange between the solvent and the surface hydrides generated by loss from surface cyclooctyls.

Under our experimental conditions, ROD(H) is present in huge excess over H(D)*, and since exchange between ROD(H) and H(D)* is fast, we can assume that ν_{-1} in Scheme II is kinetically negligible. When cyclooctane-d_0 is subjected to these experimental conditions, it does not incorporate deuterium; therefore, ν_{-5} is also negligible. Cyclooctane-d_{16} is the most abundant isotopomer of cyclooctane produced from the reduction of both *cis*-cyclooctene and COD in EtOD under MTL conditions (Figure 1). In order for perdeuteration to occur, the isotopic exchange of hydrogen between the surface of the catalyst and the protic solvent (step 2) must be fast relative to all other steps in Scheme II. Values of d_{av} for reductions in ROD therefore provide a measure of the rate of activation of the C–H bonds of the surface alkyls (e.g., ν_1) relative to the rate of their reductive elimination as alkanes (ν_5). We believe that this conclusion is true for both kinetic regimes, and all protic solvents (perhaps with the exception of water/THF at pH(D) = 13) and substrates studied here.

(4) Surface alkyls derived from unsubstituted olefins undergo faster C–H bond activation (relative to reductive elimination) than those derived from substituted olefins. Using values of d_{av}, we cannot directly calculate values of $\Delta G^{\ddagger}$ for C–H bond activation of surface alkyls. We have shown, however, that values of d_{av} from reductions in the MTL regime (at a given temperature) reflect the reactivity of surface alkyls toward C–H bond activation.

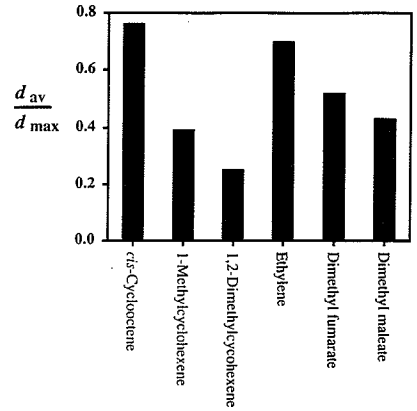

Figure 5. Plot of d_{av}/d_{max} vs substrate for the reductions of several olefins using D_2 and ethyl alcohol-*d* under MTL conditions.

Figure 5 plots d_{av}/d_{max} vs substrate for the reductions of several olefins using D_2/EtOD under MTL conditions. The largest values of d_{av}/d_{max} are generated from surface alkyls that are the most reactive toward C–H bond activation: cyclooctyl* and ethyl*, the unsubstituted surface alkyls. From this limited set of data, it is impossible to draw any conclusions regarding the relative importances of α,α-, α,β-, and π-allyl formation on the surface.

In a previous report, we argued that the incorporation of excess deuterium in the reduction of unsubstituted cycloolefins increased as a function of the strain energy in the product cycloalkanes.[49] It is difficult, however, to draw a similar correlation with substituted cycloalkanes: the deviations from symmetry probably provide potential wells in which the surface alkyls become trapped; as a consequence, the contribution of strain energy to the incorporation of deuterium is not detectable.

(5) The rate of C–H bond activation (relative to the rate of reductive elimination) is faster in the MTL regime than in the RRL regime, probably because the temperature is higher. The data in Tables V–VII and IX establish that, for both kinetic regimes (MTL and RRL), F_D is similar for reductions using D_2/ROD and H_2/ROD, and $F_D \approx 0$ for reductions carried out in D_2/ROH. That is, the values of F_D follow a consistent pattern within each kinetic regime (although the absolute concentrations of H(D)* are probably very different in the two regimes). The reductions under RRL conditions are conducted at lower temperatures than are those under MTL conditions (typically −20 vs 40 °C). This difference in temperature apparently does not affect the efficiency of the isotopic exchange of hydrogen between protic solvents and the surface of the catalyst: if it did, the patterns in the values of F_D would differ in the two regimes. Nevertheless, in reductions in alcohol-*d* and D_2O/THF, more deuterium is found in the product alkanes under MTL conditions than under RRL conditions. Since the efficiency of the isotopic exchange does not vary between kinetic regimes, the rate of C–H bond activation (relative to the rate of reductive elimination) of surface alkyls is *faster* under MTL conditions than under RRL conditions. We attribute the difference in the rate of C–H bond activation in the two regimes to the difference in temperature between them: the rate of C–H bond activation of hydrocarbons on platinum should increase with temperature.[55]

(6) In the MTL regime, polydeuteration results rather than exclusive perdeuteration. For reductions of olefins in ROD under MTL conditions, polydeuterated rather than exclusively perdeuterated alkanes are the products. Our comparisons between RRL and MTL conditions, and between reductions under MTL conditions at various temperatures show that the incorporation of excess deuterium depends strongly on the reaction conditions, in particular, the temperature and the pressure of hydrogen (deuterium). We believe that the incorporation of excess deu-

(54) Since we observe only relative rates of exchange and reduction, a faster rate of reduction of *cis*-cyclooctene at pD 13 than at other values of pD could explain the low values of d_{av} at pD 13. The percent conversions reported in Table VII argue against this hypothesis: percent conversions were generally lower at pH(D) 13 than in the range pH(D) 1–10; therefore, the rates of reduction at pH(D) 13 are apparently slower than at the other values of pH(D). We do not, however, rule out poisoning of the catalyst at pH(D) 13.

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terium can be increased (ultimately to the exclusive production of perdeuterated alkanes) by performing the reductions at higher temperatures (thereby increasing the rate of C–H bond activation and, thus, exchange) and lower pressures of H_2 or D_2 (thereby decreasing the rate of reductive elimination) than those used in the work presented here.

(7) In the synthesis of isotopically labeled compounds, the extent of incorporation of deuterium is maximized under MTL conditions and minimized under RRL conditions. Our comparisons between MTL and RRL regimes allow us to define reaction conditions that will be useful in the synthesis of isotopically labeled compounds. The reductions of olefins carried out in ROD give maximum incorporation of deuterium at low pressures of H_2 (or D_2) and high temperatures; minimum incorporation of deuterium occurs with high pressures of H_2 (or D_2) and low temperatures. The techniques demonstrated here should also be applicable to the incorporation of tritium in organic compounds.

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